Planetary Integrated Camera-Spectrometer (PICS): a new approach to developing a self-sequencing, integrated, multiwavelength instrument

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ABSTRACT

The Planetary Integrated Camera-Spectrometer, 1'1('S, is an highly integrated sensor system which performs the functions of three optical instruments: a near infrared (11<) s}o['et]'[)]llc't('r, a visible imaging camera, and an ultraviolet (UV) spectrometer. Integration serves to minimize the mass and power required to operate a complex suite of instruments, and automatically yields a comprehensive data set, optimized for correlative analysis. This approach will be useful for deep space missions such as Pluto Express and will also enable Galileo/Cassini class remote observations of any object within the Solar System. In our baseline concept, a single set of lightweight multiwavelength foreoptics is shared by a UV imaging spectrometer (80 spectral channels 70-1.50 rim), a two-CCD visible imaging system (shuttered in two colors 300-500 nm and 500-1000 nm), and a near-1]< imaging spectrometer (256 spectral channels 1300-2600 rim). The entire structure, including its optics, is built from silicon carbide (SiC) for thermal and dimensional stability. in addition, there are no moving parts and each spectrometer covers a single octave in wavelength. A separate port is provided for measurement of a UV solar occultation and for spectral radiance calibration of the 11< and visible subsystems. The integrated science that the PICS will yield meets or exceeds all of the Priority-1A science objectives, and many Priority-1B science objectives as well, for the Pluto Express Mission. This paper provides details of the 1'1('S instrument design, fabrication and testing, both at the sub-assembly and the instrument level. in all tests, including optical, thermal vacuum, and structural/dynamics, the PICS hardware prototype met or exceeded functional requirements.

1. THE PICS CONCEPT

The Planetary Integrated Camera-Spectro meter, PICS, is a sensor system that combines the functions of three optical instruments: a near infrared (IR) spectrometer, a visible imaging camera, and an ultraviolet (UV) spectrometer. This integrated approach will be useful not only for deep space missions, such as Pluto Express, but will enable remote optical observations of any object within our solar system. Integration serves to minimize the mass and power required to operate a complex suite of instruments and yields a data set optimized for correlative analysis. The design of the PICS was based on a set of observational sequences for the UV, visible, and IR channels, which met the science 1 A objectives for a flyby of Pluto/Charon. A single sensor system was designed, housing all three channels, with shared redundancies in the integrated electronics. This integrated approach results in a reduction in mass, power, and volume of 15-30x compared to Voyager, while leading to an *increase* in sensitivity of 10-1000x. Moreover, it improves reliability and results in substantial cost savings in manufacture, integration, test, and operations.

From the outset, the objective of the PICS approach was to simplify the system as well as to minimize the mass and power of the instrument by maximizing the level of its integration. That is, wherever possible, the instrument's four channels would use common optics and electronic signal paths. "Thus, a single primary mirror was used for all wavelengths, avoiding the need for duplication of this high mass element. The need for a signal-to-noise ratio of 100:1 in the infrared and visible channels mandated the choice of a primary aperture of 10 cm diameter. At this diameter, PICS performance will be limited by the background (not the instrument). For the IR detectors, which require cooling to ≤90K, the detector and its radiator were designed to form a mechanically integrated subassembly. The optics were designed to avoid the need for a focusing subassembly. A one octave limit was accepted on the range of each spectrometer, simplifying design and avoiding the need for sorting filters. The PICS instrument parameters are summarized in Table 1. The design performance of the PICS instrument as a function of wavelength over the combined UV, visible, and near IR spectral ranges is illustrated in Figure 1.

Table 1. PICS Performance Parameters.

	UV	Vis (Blue)	Vis (Red)	IR
Wavelength Range	70-350 nm	300-500 nm	500-1000 nm	30[)-2600 nm
Aperture diameter	1(1 cm	10 cm	10 cm	0 cm
Effective Focal Length	?0.0 cm	75.0 cm	75.[) cm	5,() cm
F/#	2.1	6.7	6.7	.7
Detector Array Size	10 x 80	1024 x 1024	1024 x 1024	56 x 256
Pixel Size (pm)	100	9.0	9.0	0
FOV (deg)	0.34x0.03	0.79x0.79	0.79 x 0.79	.6x0.03
IFOV (μrad)	500	13	13	3.3
Plate Scale (μrad/mm)	4.76	1.33	1.33	.33
Spectral Resolution	1.011111			0 nm
Sampling Interval	0.5 nm			nm
SNR	Photon noise limited	Photon noise limited	Photon noise limited	hoton noise imited
Typical Exposure Time	30-3000 sec airglow 0.1 sec solar occultation	>1 sec	>1 sec	>3 sec

Other constraints were adopted in keeping with the nature of the mission itself. The PICS instrument will have to maintain its integrity over a wide range of temperatures, from 280K near the Earth to 40K-60K at 30 AU from the Sun. It was necessary to choose a structural material that was dimensionally and mechanically stable over time, chemically non-reactive, structurally strong, and manufacturable. Based on these requirements, it was decided that the entire instrument, structure and optics, would be made of Silicon Carbide, SiC.

To achieve the necessary level of integration, PICS was designed to support an integrated timeline, that is, one in which data collection is optimized when the channels are operated in a time multiplexed fashion, with only one of the four channels collecting data at any one time. The single signal chain (with a redundant, powered-off signal chain available for increased reliability) reduces the power required to run the detectors. This feature produces a comprehensive mission data set and enables mission planners to make the greatest use of the few precious hours of planetary flyby and avoid the sequencing problems of earlier missions, such as Voyager and Galileo.

The validation of the PICS low-mass, low-power concept was achieved by the fabrication and testing of hardware breadboards. Optical performance tests were conducted which validated that the breadboards met functional specification for all channels across the full range of expected thermal conditions. Thermal and vibrational tests were performed to show that environmental conditions normally encountered during launch and cruise would not degrade performance. These tests were designed to focus on and emphasize the high-technology aspects of the PICS concept. Analysis of the results shows that all optical, thermal, and structural properties fall within design specifications. Flight testing of a PICS prototype is planned as part of the New Millennium Program DS-1 Mission.

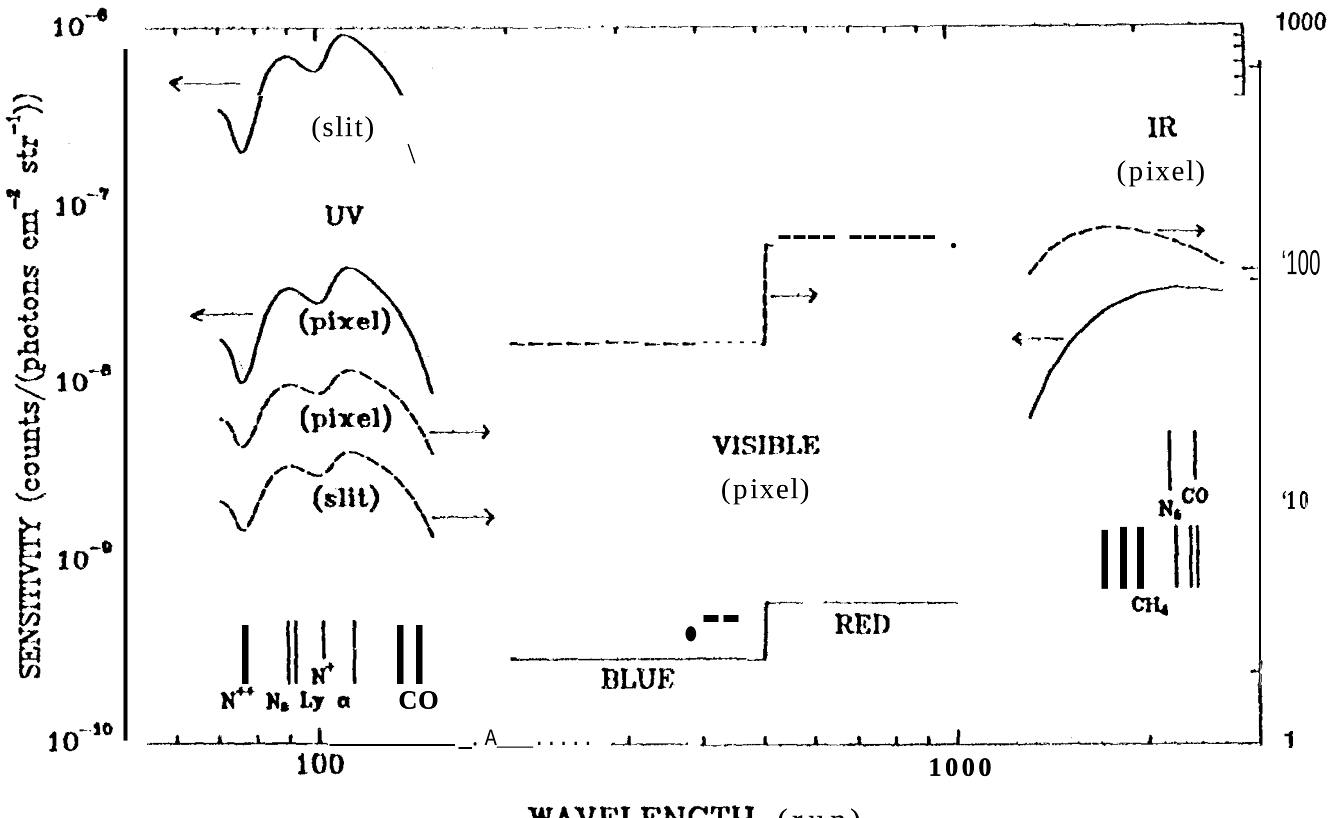


Figure 1. Design performance specifications of the PICS instrument. The solid curves show sensitivity and refer to the scale on the left vertical axis. The dashed curves show the SNR and refer to the scale on the right.

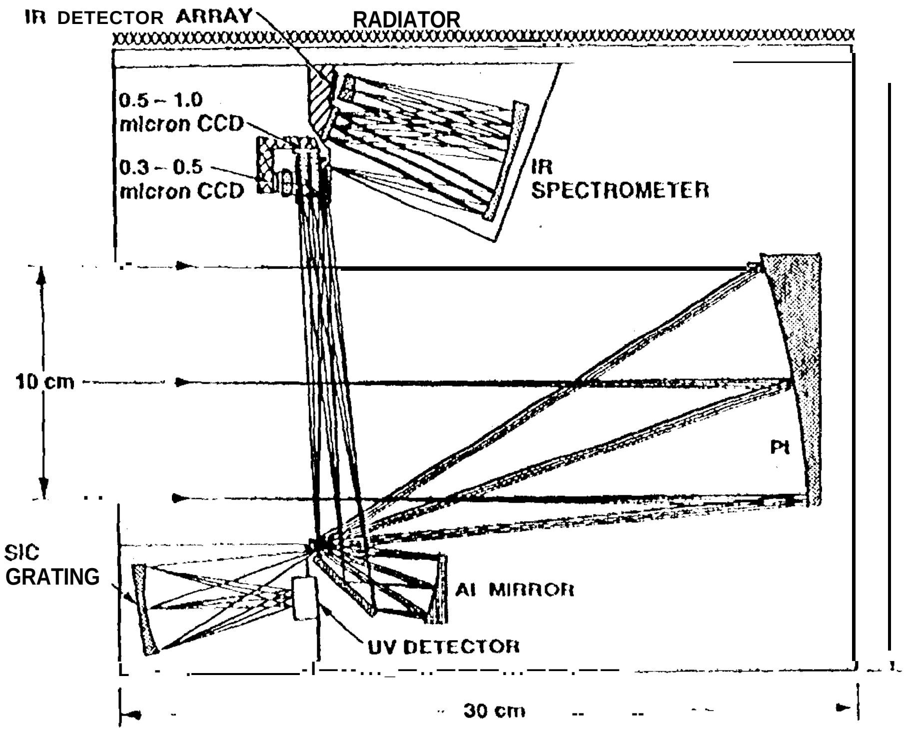
2. OPTICAL SYSTEM

The PICS optical system consists of a two-color camera, an infrared imaging spectrometer, and an ultraviolet imaging spectrometer. These systems share a single off-axis Gregorian telescope as shown in Figure 2. The two camera systems occupy the same field position; the spectrometer fields are adjacent to the cameras.

Telescope system. The primary and secondary mirrors for the telescope are off-axis sections of rotationally symmetric aspheres, to enable fabrication by diamond turning with post-polishing. An advantage of the off-axis telescope design is that it provides better image contrast than on-axis designs in which an obscuring secondary mirror contributes diffraction and scatted light. in the UV spectrometer channel, light from the primary mirror is focused directly onto the UV entrance slit. "1'here is, therefore, only one reflection prior to entering the spectrometer. The off-axis UV spectrometer utilizes an aloe'rrati[~ll-cc)lrccted toroidal diffraction grating. A fold mirror reflects the fields for the visible camera and infrared spectrometer to an al~ll~~il~tllll-coated secondary mirror.

Camera system. The light from the telescope secondary is folded across the telescope to the focal plane assembly, where two CCDs are located. 'J'here a dichroic beamsplitter cube splits the light to the two focal planes. Two field flattening lenses in front of the CCD focal Planes correct the telescope's field curvature. Raytrace results show that cliff raction-limited performance is achieved over both CCD fields of view.

Infrared imaging spectrometer. The infrared imaging spectrometer slit is off-axis with respect to the CCD fields (Figure **2).** This enables the light for the infrared imaging spectrometer to be split off after the dichroic cube by a small mirror (a small aluminized prism bonded to the cube)



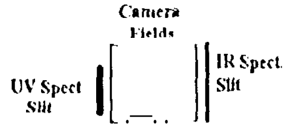


Figure 2. Optical raytrace of off-axis Gregorian multiwavelength telescope. Inset at right shows schematic layout of the camera and spectrometers' fields of view.

Ultraviolet imaging spectrometer. The need for sufficient system reflectance in the far ultraviolet spectrometer was the major driver in developing its design configuration. Reasonable reflectance was achieved by sharing only one reflection with the other systems, namely the telescope primary mirror, which is platinum-coated to provide for ultraviolet reflectance. The grating in the ultraviolet spectrometer is silicon carbide coated to provide good reflectance. Thus, the UV spectrometer design utilizes only two reflective elements: the primary mirror and the grating.

The toroidal grating (1400 grooves/mm) focuses the light onto an intensified CCD detector. The CCD is of the same type as that used in the visible channel to simplify data acquisition and control electronics. The intensified CCD detector consists of a single microchannel plate (MCP) coupled to a phosphor output, which feds the CCD. The toroidal grating is holographically corrected to minimize stray light and produces a flat image plane on the MCP. Raytrace results show spot sizes ≤ 0.1 mm over the focal plane.

The decision to couple the UV spectrometer to the visible and IR channels by sharing a single primary mirror, rather than by using a completely separate UV channel, was made to minimize mass and complexity and to minimize power consumption. Some efficiency is sacrificed because the platinum coating used on the primary mirror has smaller UV reflectance (by a factor of ≈ two) than some other materials (e.g., SiC). However, the large area of this mirror (relative to that possible by using a separate UV channel) more than compensates for the lower reflectance.

An important aspect of the UV spectrometer is driven by the requirement that PICS observe the occultation of the Sun through Pluto's atmosphere. To achieve this, a small fold mirror is used to introduce sunlight into the main telescope beam. This mirror limits the sunlight collecting area of the spectrometer so that saturation of the detectors by the bright Sun is not a problem. Moreover, it enables the alignment of the UV occultation port with respect to the spacecraft's high gain antenna, so that solar and radio occultations can be observed simultaneously.

3. STRUCTURAL CONFIGURATION

The structural configuration of PICS, developed in collaboration with SSG inc. of Waltham, Mass., is shown in Figure 3. The telescope has a triangular shaped optical bench housing the three highly integrated optical systems. The triangular construction offers leverage in achieving a lighter and stiffer optical bench, in which the off-axis telescope optics (except for the primary mirror and sunport pickoff mirror) and detectors can be conveniently integrated and aligned externally.

While all the optical elements and detectors of the UV spectrometer and visible camera are mounted directly on the 150K telescope optical bench, the 90 Kelvin infrared spectrometer is packaged in an integrated detector-radiator assembly. The IR bench is mounted to the telescope by means of three pre-stressed fiberglass band supports providing thermal isolation. The fiberglass supports are arranged in such a way that the IR spectrometer's entrance slit is athermalized (not thermally connected) relative to the telescope optical bench,

One of the innovative features of the PICS telescope design is in the use of monolithic material Silicon Carbide, SiC, for both the structural and the optical elements, The use of SiC is an emerging technology approach for future instrument design and it offers several important advantages. First, it has a high specific stiffness, allowing for thinner and lighter design. Second, its optical performance is equal to that of glass, but with a much higher strength and fracture toughness. Third, it has good thermal stability at cryogenic temperatures. And fourth, it has physical stability over the mission lifetime.

The entire telescope assembly is mounted onto the warm electronics chassis cinematically by means of three Vespel bipods which also provide thermal isolation. The electronics chassis directly under the telescope optical bench provides the detector electronics the shortest possible wire length. The electronics chassis serves as a transition structure to the spacecraft mounting surface. Vibration and shock isolation will be achieved with commercial mounts using silicone elastomer.

4. RADIATOR/DETECTOR MOUNTING

A multistage radiative cooler best fits the mission environment for PICS. The detector power dissipation of this cooler is 10 milliwatts. This approach provides an infusion of new technology to help meet the severe mission constraints of power, mass, and cost for outer planet missions such as Pluto Express. This radiator is integrated into the instrument design and not a separate additional component. The IR detector radiating surface is an outward facing component of the instrument enclosure. The optical design is configured in such a way that the IR detector mounts directly onto the inner surface of the radiator. The support structure for the detector/radiator subassembly is part of the optical bench and provides the necessary thermal isolation. The configuration is such that the detector can be made easily accessible for ground testing and Possible last minute detector replacement. All non-radiating surfaces will be covered with multilayer insulation (MLI) to minimize radiative heat transfer.

The instrument is divided into three temperature zones, each with its own radiator, to accommodate the required component temperatures: these three zones include the optics, the electronics, and the IR detector temperature zones.

Optics temperature zone. The optics will be maintained at about 150K to minimize the heat radiated from the optical elements to the IR detector and to Provide a relatively cool background for the IR detector radiator. Along with the optical elements and CCDs, this temperature zone includes the optical bench structure. Since there is little or no heat

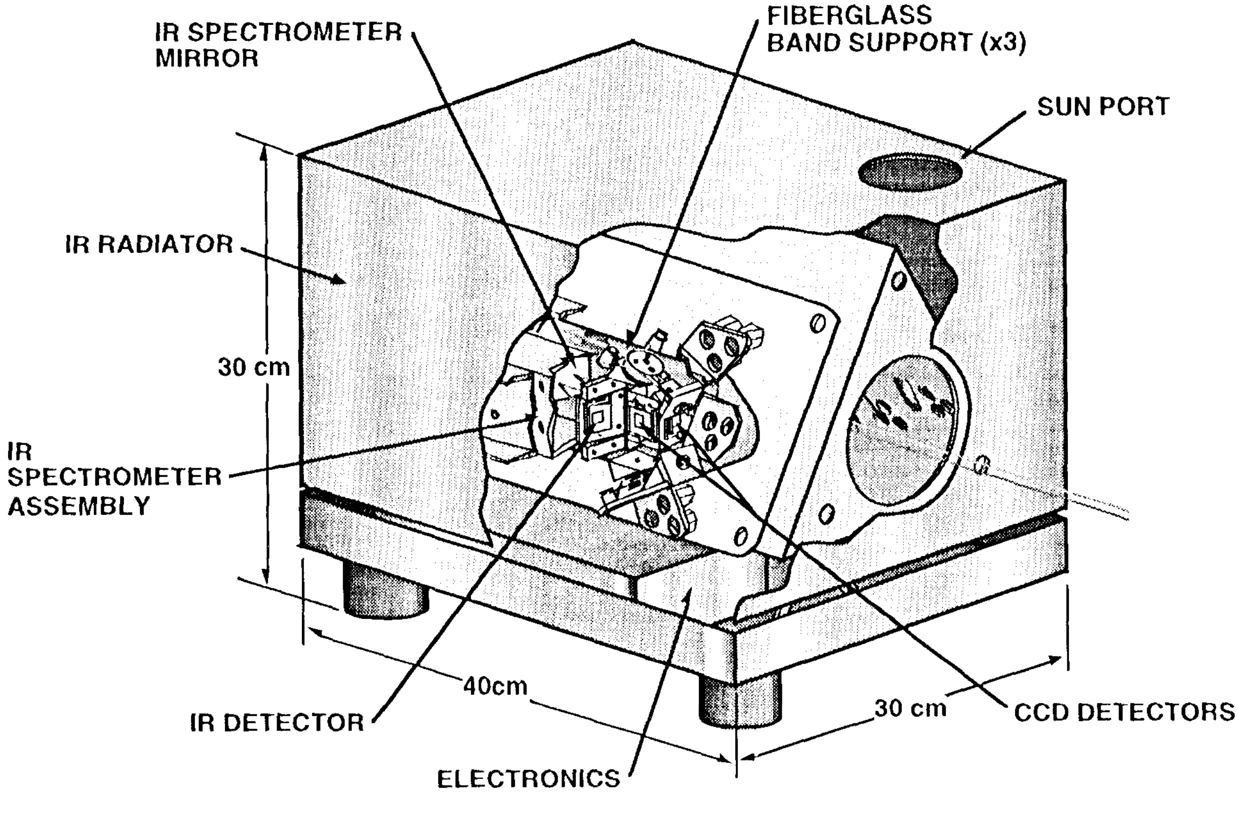


Figure 3. Structural configuration of the Planetary Integrated Camera-Spectrometer, PICS, viewed from the IR spectrometer side.

dissipation in this zone, the temperature will be maintained by a balance between the heat leakage from the warmer electronics zone and the heat radiated from the surface of the instrument facing the planetary target body.

Electronics temperature zone. The electronics are maintained at 230K to 270K. The electronics will be mounted on a plate located between the optical bench and the spacecraft. This plate will be thermally attached to the warm electronics radiator which, in turn, is coplanar with the optical opening and shares its field of view. Because the structure and the majority of the box is included in the optics temperature zone, the electronics and the plate on which it is mounted will be radiatively and conductively isolated from the structure which is at the optics zone temperature. The temperature of the electronics zone will be held to low levels to minimize heat leakage into the other zones, as well as to minimize the long term outgassing products that could Condense into colder optics and detectors.

IR Detector temperature zone. The IR detector subassembly will be maintained at a temperature of ≤90K by directly mounting to the IR radiator plate; the entire plate will be mounted to the telescope structure with a fiberglass band support system to minimize heat conduction. The attachment of the cold IR detector/radiator subassembly to the 150K optical bench forms a two-stage radiative cooler for the IR detector,

5. INTEGRATED ELECTRONICS

The same signal chain serves all channels of the PICS instrument, operating sequentially. in this way, the "excess baggage" of duplicated electronics for each channel is avoided. The electronics for the visual, UV, and IR imaging subsystems draw heavily upon JPL's experience. However, state-of-the-art electronics packaging, hybrids, and gate arrays are employed to minimize mass and size. The CMOS gate arrays and the judicious selection of analog components reduces the power requirements.

The PICS functional block diagram is shown in Figure 4. Three electronic modules provide the control, timing, and signal Processing required by the imaging subsystem. The Instrument Control and Input/Output (ICIO) module has been implemented in a CMOS gate array. Detector timing, integration control, detector readout, command and data interfaces are implemented within the instrument control functional block. CCD drive level translation, bias, and preamplification are provided by the Clock Drive (CD) hybrid. Three CD modules are required: one for each CCD detector in the two visible channels and the UV channel. Clock buffering and preamplification for the IR array is provided by a discrete subset of the CD electronics. Output signals from the detectors are multiplexed to the video signal processor hybrid. The hybrid module provides all required gain, clamping, and

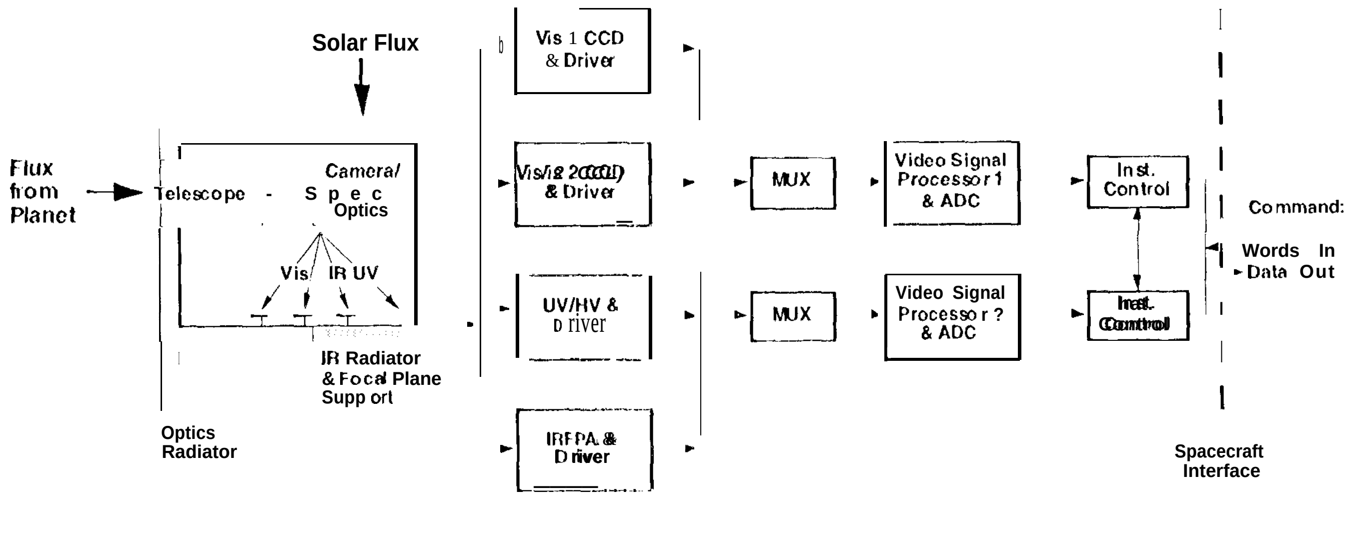


Figure 4. Functional block diagram for the Planetary Integrated Camera-Spectrometer

sampling prior to digitizing the detector video output signal. The signal chain interfaces with a low power analog-to-digital converter.

'1'0 assure mission success, redundancy is designed onto the flight imaging subsystem electronics. Power will be provided by a dual bus system. The focal plane instruments (~~11 and HgCdTe) will be partitioned such that in the event of a power failure on one bus, at least two of the instruments will survive. A standby (powered-down) CI) and ICIO is incorporated to provide a backup capability for the instrument. If a failure occurs in the signal processing or control, this backup circuitry will be turned on and multiplexed into the data path. With the backup circuitry in operation, the instrument performance will not be compromised. in order to meet science goals, detector pixels will be processed at a 300 K} Iz rate. The electronics for the instruments requires less than 5.4 watts at this processing rate.

6. INFRARED FOCAL PLANE

6.1 Requirements

The science requirements for the infrared imaging spectrometer channel of the PICS instrument, and the strict limits on instrument mass and sire, impose several difficult demands on the IR focal plane. These demands include:

Capability for SNR>100 in all spectral channels. The extremely low levels of reflected sunlight in the outer Solar System, along with the small telescope aperture, demand a focal Plane with a high quantum efficiency and low read noise.

High spatial and spectral resolution. The need for 10 nm resolution wavelengths from 1.3 to 2.6 mm, as well as ≈4 km ground spatial resolution at closest approach, coupled with the pushbroom design chosen for the imaging spectrometer, demand at least a 256 x 2.56 staring IR focal plane.

Radiation hardness. The major source of radiation for a mission to the outer Solar System is not from the sun or trapped radiation belts, but from the spacecraft's plutonium-powered I< TG power units. Current estimates are that the focal plane array would be subjected to 20 krads on a journey to Pluto, mostly in the form of RTG neutrons.

Relatively high operating temperature. The small mass, power and volume envelope that PICS must fit into eliminates the use of active coolers; small passive radiators must supply the cooling needed by the focal plane. The PICS integrated cooler is designed to provide 10 mwatt cooling at 90K, the lowest temperature practical within the spacecraft constraints To allow the IR focal plane array to have low dark current at these temperatures, the cutoff wavelength of the photo diode array must be matched to the longest wavelength of interest (2.6 μmeters).

Strong heritage to proven IR focal plane arrays. No existing focal plane could meet all these requirements, so a design goal was to base the PICS IR focal plane array on an existing design and make as few modifications as necessary to fulfill the instrument objectives.

6.2 Architecture

The PICS focal plane readout represents an evolutionary advancement on the very successful Near Infrared Camera and Multi-Object Spectrograph (NICMOS-3) readout developed by the Rockwell Science Center, Thousand Oaks, CA. This focal plane was created for the NICMOS instrument, a Hubble Space Telescope second generation replacement package. NICMOS-3 focal planes, with 2.5 mm cutoff MCT diodes, have been utilized for several years now in ground-based astronomical cameras at the world's leading observatories. This experience, along with continued developments at Rockwell, provided a solid base for creation of a focal plane design to meet the stringent PICS goals.

The PICS readout is based on silicon CMOS circuitry. The PIC-NICMOS (PICNIC) die, unlike the NICMOS-3 readout, arc being fabricated at a foundry with a radiation hard CMOS Process, and the unit ccl] has been designed with radiation hardness features. The 20 krad specification imposed by the spacecraft will be met easily by the chosen CMOS process. Typical scenarios allow the focal plane to be "warm" (≈300K) during most of the voyage, except for checkout periods. This warming anneals out radiation damage due to ionizing particles, without degrading the performance of the focal plane array. Since the instrument will only be cold during the final phase of the journey, the PICS team anticipates very little degradation due to ionizing radiation.

To meet the high defectivity demanded for reaching SNR>100 with the small diameter optical system, a very low read noise is desired. The PICNIC achieves low read noise (≈30 electrons, input referred). in addition, an aspect of the NICMOS-3, referred to as the "reset anomal y," has been eliminated. The resent anomaly involves the instability of the output level immediately after the reset pulse is removed. The PICNIC unit cell with one transistor removed from the NICMOS design, is free of this anomaly,

This change benefits the focal plane in several ways: a lower read noise (modeled to be ≈18 Electrons), greater operating efficiency (no dead time on useless reads), and the option of reading the array uncorrelated (estimated noise 100 electrons), for situations where long integrations will permit high SNR without CDS, permitting a reduction of two in the data storage requirements. The die yield is also enhanced by the simpler unit cell architecture.

7. HARDWARE BREADBOARD TESTS

The validation of the PICS low mass, low power concept was achieved by the fabrication and test of hardware breadboards. Optical performance tests were conducted to validate that the breadboards met functions] specifications. Thermal and vibrational tests were performed to show that environmental conditions normally encountered during launch and cruise would not degrade performance. The design and testing of breadboards was limited by funding and schedule constraints, 1 Ience, only a selected set of demonstrations was planned. These were selected to test the high technology aspects of the PICS concept.

7.1 Objectives

Mass. A goal of 2800 grams was establish for the mass of the optical bench assembly. While very aggressive, this choice was not considered the ultimate that could be attained, but rather it was consistent with, and bawd on, several factors These include the characteristics of the silicon carbide material as described above (high specific stiffness and thermal stability), the level of prior as well as parallel hardware demonstrations and the accelerated program schedule. As a result of the latter, it was determined that only design approaches previously validated in SiC hardware would be chosen.

Wavefront performance. A goal of 1-2 waves (peak-to-valley at 0.63 microns) single-pass transmittal wavefront was adopted to demonstrate wavefront performance as a function of temperature. This compromise accuracy was chosen to permit maximum use of automated finishing processes. This accuracy at the anticipated 150K operating temperature is adequate to provide compatibility with the CCD focal plane and sufficient sensitivity to effects of the extended thermal range. It also provides a pathway to demonstrate improved wavefront performance at a lower mass objective.

7.2 Approach

The two objectives stated above determined our app roach in the design and fabrication of the prototype. The system concept emphasized the thermal and low mass considerations. The same material is used for all the reflective optical components and structural elements to provide passively athermal system operation. A triangular cage approach provided several advantages: minimum mass for the degree of stiffness provided while permitting access to optical assemblies from outside the structure. This is an important consideration given the density and small size of the optical elements. Minimum cross-sectional thicknesses consistent with material stiffness, fixturing complexity and process limitations were employed.

Mass reduction considerations also drove the selection of integral mirror /mount designs for many of the optical components. Such a concept provides lighter weight, fewer and simpler interfaces, and reduced sources of alignment error. The mounts were integrally fused with the mirr or substrates with invar feet bonded or brazed to provide interfaces to threaded invar buttons on the structure. The latter were attached to the structural elements in a similar fashion.

Other design and process decisions for the PICS hardware were driven by producibility. For the choice of a structural material, a form of the silicon carbide was chosen, which provided a high modulus of elasticity while minimizing brittleness and fracture toughness limitations. Aspheric substrates were fabricated to near net shape and then deposited with tenths-o - millimeters of pure silicon. As specialized developments in the deposition technology, a diamond machining compatible layer was achieved. This permitted a precision starting point for renal, aspheric polishing operations and the incorporation of precision geometrical references into the mirror's mechanical features for ease of system alignment. Reflective coatings for the appropriate wavebands were then applied to the optically finished silicon layer. Because of its use as a 3-5 micron refractive material, the coatin g of silicon is well understood within the optical industry, including cleaning processes and deposition-compat ible materials. The thermal expansion coefficients of Si and SiC arc virtually identical.

The ease of producibility also influenced the selection of the alignment design concept. in order to reduce risk and maintain schedule, extended range of component positional and attitude adjustment were given Priority. A mass penalty was paid because of the resulting size and number of invar buttons and shims, but the validity of the technology path to be demonstrated was not compromised by this select ion.

The flat optical elements arc made by directly polishing the silicon carbide substrates, since increased lap time was less a cost and schedule issue for such a configuration. Reflective coatings were also successfully applied on these elements. Best-fit spherical substrates were manufactured for the UV channel toroidal gratings prior to polishing at Tinsley, grating replication at American 1 lolographic, and application of CVD silicon carbide by GSFC.

7.3 Results

7.3.1 Optical tests

Fabrication and assembly. The PICS structure and optical components for the visible channel were fabricated. The flats were polished to 0.05 visible wave peak-to-valley levels of surface accuracy. The major contributors to system wave front performance are the primary and secondary mirrors. The former was post diamond-t u ning polished to 0.50 wave }wak-to-valley at the surface. The secondary mirror achieved 0.32 wave performance. The primary visible channel is currently in integration and has been aligned to 1.60 waves peak-to-valley single pass transmittal wavefront per the interferograms and digital data reduction shown in Figure 5. This full -aperture performance is within approximately 0.4 waves of the levels defined by root-sum-squaring the

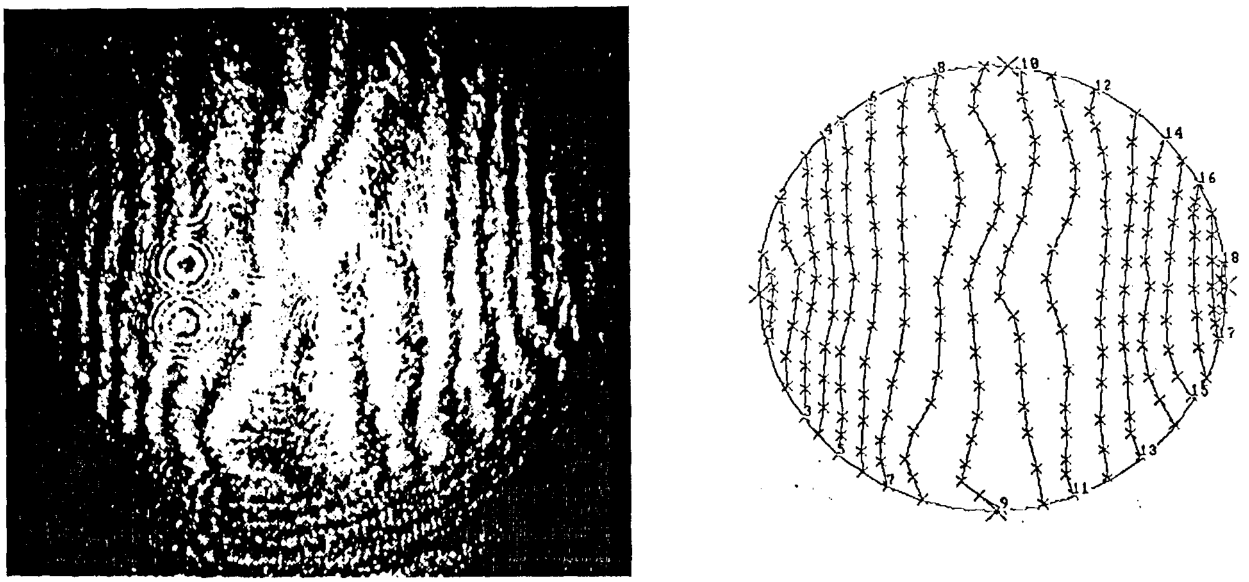


Figure 5. PICS visible double pass transmitted wavefront interferogram (left) and corresponding digital data reduction.

contributions from only the primary and second ary mirrors. Over the central 90% of the aperture, the performance is better than one wave peak-to-valley. This significant improvement is the result of the major error contribution coming from roll-off seen on the edges of the primary mirror. For future iterations, a more rigid fixturing scheme at the mirror periphery during the finishing process will allow imaging quality performance to flight units. The optical components and structural elements for the infrared channel arc currently in the manufacturing stage. Optical finishing is being performed prior to application of reflective coatings. The U V grating is complete and the IR grating is now being polished prior to grating replication and CVD SiC application.

Visible imager. In its present configuration, the PICS prototype has onl y one visible CCD focal plane. Hence, the prototype is strictly a monochrome imaging instrument. To obtain color images samples were illuminated sequentially with red, green, and blue light. The light source was a high-intensity halogen lamp, with the light directed through color-separation filters.

Since PICS is designed for remote imaging, a refractive collimator was employed to enable the imaging of small samples at a close distance. Two rock samples ("lava" and "granite") were imaged under vacuum conditions onto the visible CCD focal plane. The samples were illuminated as described above and the sequential monochrome image data were recorded using the PICS instrument and an ancillary data system. These images are 860 by 400 pixels in raw foı mat (8-bit data). No flat-field or dark current images were obtained. Full color images were reconstructed by adding the individual color images together. Although there are slight misregistrations, the image quality demonstrates that the instrument is capable of obtaining high-quality color images. These images are presented in Figure 6.

Infrared imaging spectrometer. The IR Bench of the PICS instrument was tested as a unit at 78.3 Kelvin. The IR Bench consists of a Silicon Carbide structure containing the entrance slit, the primary mirror, the planar grating which acts as the secondary, a field flattening clement and the NICMOS-3 detector. One quadrant of the 256x256 element array was used in these tests. Mechanical realignment of the spectrometer was performed at room temperature and the reassemble structure was placed in a 10 inch diameter test dewar. The dewar was of a double reservoir construction with two light shields, a filter wheel and a CaF_2 entrance window. Data was acquired through the PICS breadboard electronics and stored on a PC. For flat field illumination the field-of-view was filled with a large Spectralon Target. Sample spectra were recorded for two cases of illumination. The first

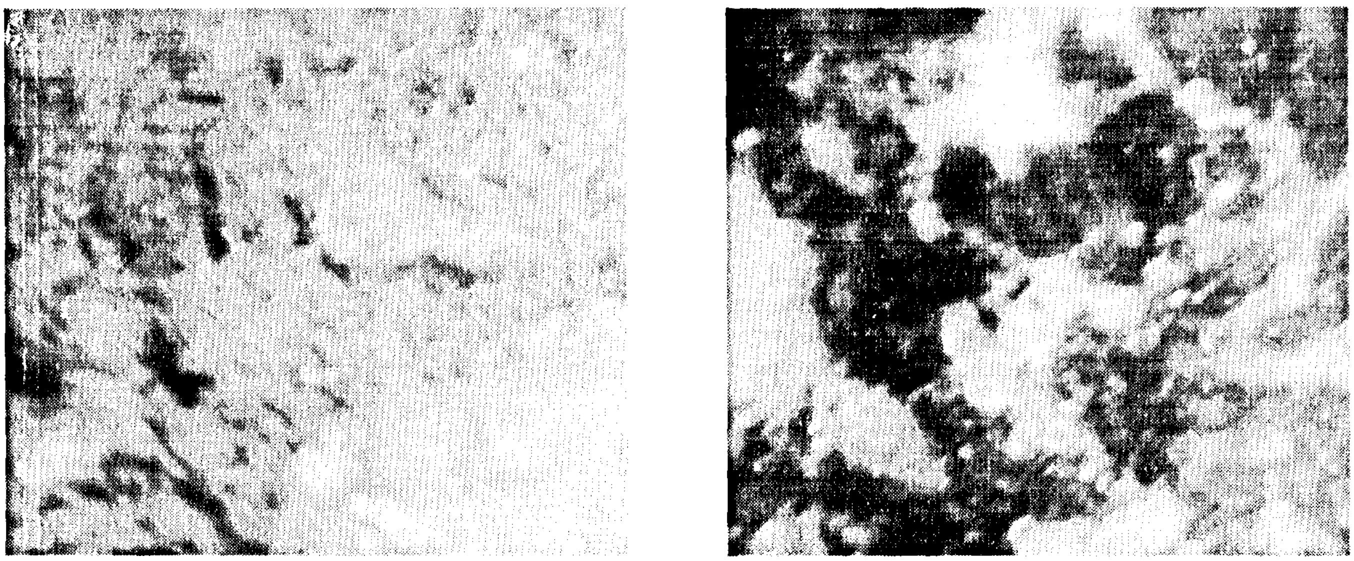


Figure 6. Visible. channel test rr.wits showing images of "lava" (left) and "granite."

(Figure 7a) shows the spectrum from a Krypton discharge lamp in reflection from the Spectralon Target. Spectral features are clearly visible in multiple orders. The second (Figure 7b) shows the spectrum of thermal radiation from the 293 K target, The spectrum is in first order, and clearly shows the detector response profile cutting off at 2.5 μmeters due to the bandgap of the NICMOS-3 HgCdTe photodiodes. To record the next series of plots, the exit silt of an Acton Monochrometer was imaged on to the slit of the PICS IR Bench with an CaF_2 lens. Care was taken to limit the ray bundles to the field of view. Data was acquired at five wavelengths. An example of an individual line spectrum is shown (Figure 7c) as well as the dispersion for the system (Figure 7d). The response seen in this figure shows that the spectrometer is linear in first order.

Structure and optics testing The PICS instrument were tested for cryogenic wavefront performance in SSG's cryo-vacuum chamber. Testing was performed at a wavelength of 0.633 μm, using a 5 in. diameter collimated bundle from a 1 .UPI /off-axis parabola collimator. The input wavefront was <0.25 waves (P-V). The PICS instrument was mounted to an aluminum spot cooler, which had liquid nitrogen cooling lines and MINCO strip heaters connected to a control-feedback loop temperature controller. Four thermocouple temperature sensors were attached to the telescope at various positions along the SiC structure and M-1 mounting plate. Five copper cooling straps connected the PICS structure to the spot cooler to aid in heat flow. To autocollimate the telescope wavefront back to the interferometer, a single retro-sphere was hard mounted to the telescope with an Invar support structure. Fringes were monitored with a CCD camera (and monitor) and captured with a thermal printer for analysis.

Interferograms were taken and analyzed at ambient conditions, at 150K, and after a 24 hour hold at 150K. The digitized and analyzed interferograms showed little change in the

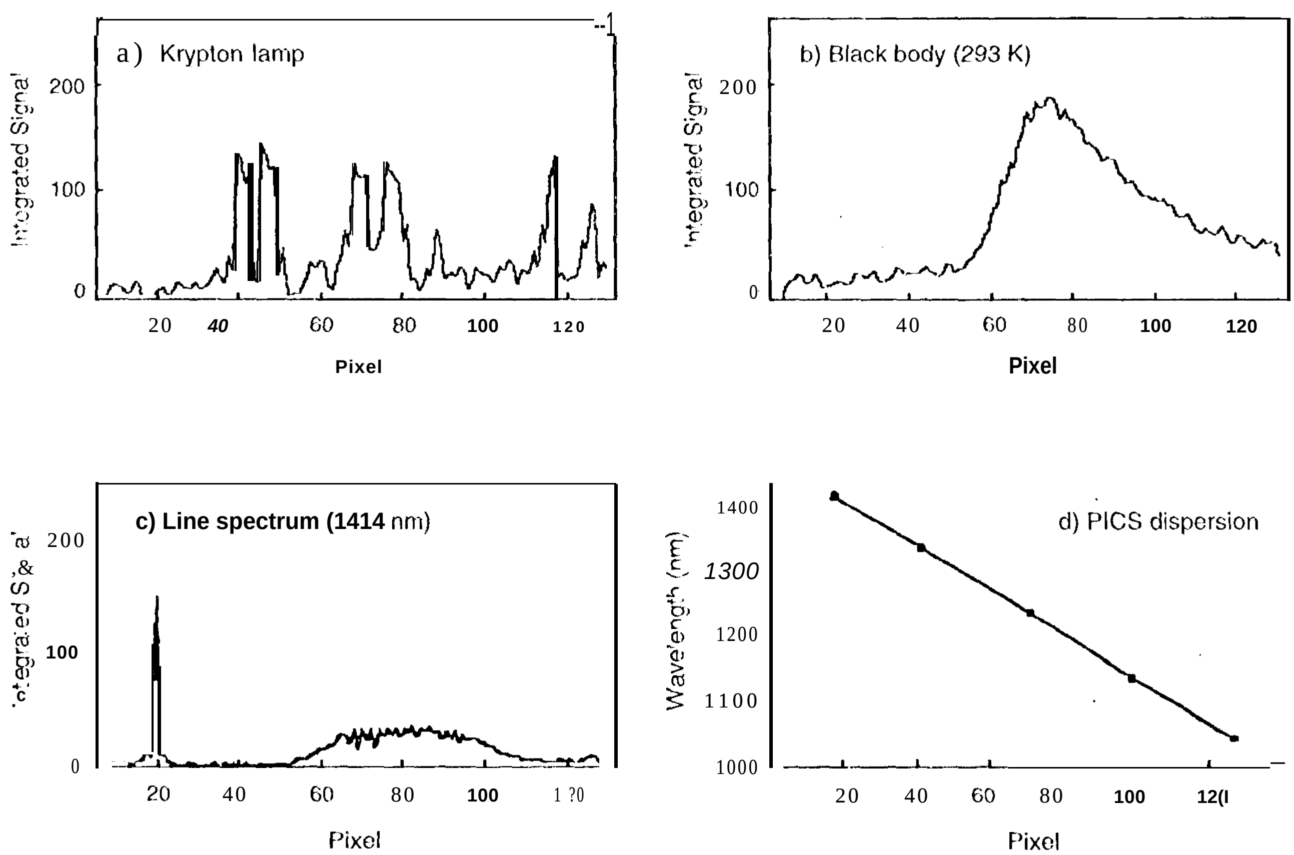


Figure 7. Spectra from the PICS infrared spectrometer.

system wavefront from ambient (1.9 P-V, 0.3 RMS) to 150K (1.75 P-V, 0.35 RMS) to the end of the 24 hour hold at 150K (1.85 P-V, 0.35 RMS). Interferograms were also taken at 200K and 165K during the cooldown, and approximately every 25K during the warmup. These have been analyzed, and initial results indicate little or no deviation from the performance stated above.

Boresight measurements between the optical system ray and a fixed reference mirror on the front aperture of the telescope (made with a Zeiss theodolite) show less than a 1 arc minute change from ambient to 150K conditions.

Integrated electronics. Tests of the PICS detector electronics have been conducted and preliminary results reported. The noise performance of the CCD detectors has been measured at 16 electrons RMS using a breadboard version of the electronics. Preliminary IR channel tests have been done with the NICMOS-3 multiplexer only (i.e., with no HgCdTe array) at 300 kpixels/sec and at a temperature of 78K. The noise performance is within specifications. Additional tests of the IR channel using the HgCdTe array are in progress.

Ultraviolet imaging spectrometer. We verified the performance of the UV spectrometer by using a test fixture to hold the primary mirror, grating, and detector in their proper positions. This

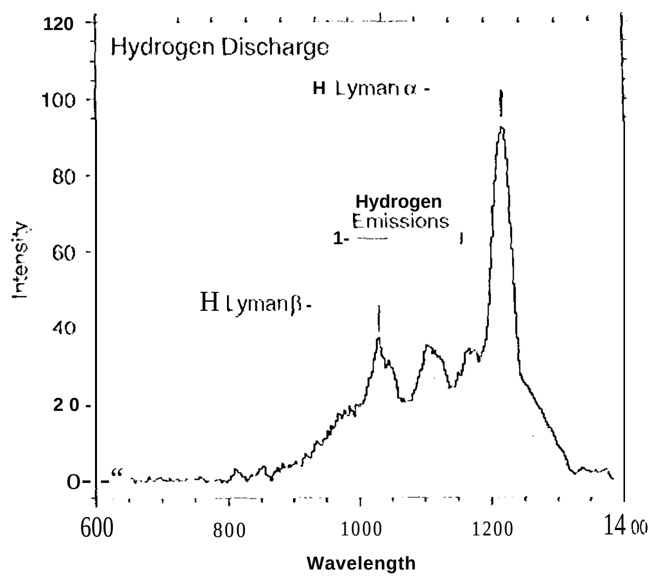


Figure 8. PICS ultraviolet spectrum.

approach permitted parallel testing of the UV components at the same time as the IR and visible components. EUV and FUV light derived from an electrical discharge in a mixture of helium and hydrogen gas entered a modified Seya-Namioka monochromator, which selected the wavelength of interest and collimated the exit beam to the test instrument. The available spectrum consisted of a mixture of the Helium 584 Å line, Lyman lines from atomic Hydrogen, and band emissions from molecular Hydrogen.

Figure 8 shows the response of the spectrograph to the zero-order beam from the monochromator. The spectral dispersion computed from the known wavelengths of the Lyman series lines agrees with the expected dispersion. The spectral response falls off rapidly longward of Hydrogen Lyman-α, because the MCP in the detector has no photocathode. in the flight unit, an opaque CsI photocathode will increase the response at the long wavelength end Of the spectrum. The spectrograph was not fully focused for this test. We also investigate the imaging performance of the spectrograph by rotating the instrument about an axis perpendicular to the UV beam.

We measured the EUV-FUV reflectivity of the primary mirror at several wavelengths in the range 584 Å to 1350 Å. Most of the wavelengths were precisely known because they were derived from noble gas discharges. The profile of reflectivity vs. wavelength has generally the same shape as the platinum reflectivity but is roughly 50% higher. At most wavelengths, we found only minor variations in sensitivity with position on the mirror.

7.3.2 **Thermal/optics** tests

The objective of the thermal tests was to verify the PICS thermal design in the Pluto thermal environment. Specifically, the tests were designed to: (a) demonstrate that the infrared radiator maintains the IR detector at 90 Kelvins, (b) demonstrate that the visible and ultraviolet CCD detectors can be maintained within a temperature range of 140-160 Kelvins, and (c) calibrate the PICS thermal model so that the results of this tests can be used to estimate performance in other thermal environments. These tests were performed at JPL, under simulated thermal and vacuum conditions. All test object ives were met.

optical tests were done in the same vacuum chambers, but under controlled conditions. The tests demonstrated that the PICS optics performed at the diffraction limit across the full range of temperatures *and during temperature transitions*. Moreover, no focus compensation will be necessary due to thermal expansion effects. A particularly impressive visual demonstration occurred on warming the PICS rapidly from operating temperature to room temperature. No change in the image quality was observed until the CCD abruptly failed to operate at close to room temperature.

7.3.3 Structural/dynamics tests

The PICS test assembly was subjected to 21 tests in order of increasing risk. Testing began on the test assembly without radiators and with a vibrational power spectrum density (PSD) of $0.1G^2/Hz$. Vibrational orientation was with respect to the y-z plane. Sequentially, radiators were added, vibrational orientation was changed to have a component along the x -axis, and PSD was increased to $0.2\ G^2/Hz$. The structural integrity of the PICS test assembly was maintained throughout these tests. This is significant, because a PSD of $0.2G^2/Hz$ is likely to be the worst possible case for Delta-II 7920/7925 class vehicle. Separate tests were performed on bulk samples of SiC material, samples of SiC that were "notched" and "buttoned" as with real structural elements. No failures were observed.

8. OTHER APPLICATIONS OF PICS

The instrument described in this paper has been developed specifically in response to an announcement of opportunity to be issued by the Pluto Fast Flyby mission. It should, however, be clear to the reader that the utility of the PICS instrument extends to a wide range of mission types. This is especially true for the foreseeable future for NASA missions, since there is a clear emphasis on the utility of missions of low-mass low-power, low-cost, and short development time, for example, as in the recently announced NASA Discovery Program.

The low electrical power required by PICS may make it especially suited for future missions to the objects in the outer Solar System. These members of the Sun's family are threatened with isolation in view of the possible exclusion (cm the grounds of expense and Programmatic complication) of nuclear technologies from use in S}-lace. The availability of PICS and other low power, low-mass, low-cost technologies may enable outer planet mission.

9. ACKNOWLEDGMENT

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